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BIOMASS POTENTIAL OF LEAFY SPURGE

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BIOMASS POTENTIAL OF LEAFY SPURGE

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ABSTRACT

This study investigates the biomass potential of leafy spurge (Euphorbia esula). Whole plant biomass yields of 3.6 to 4.9 dry weight tons per acre were obtained from late summer harvests of wild stands in southcentral Montana. Shoot biomass comprised 70% of the harvest with the remainder derived from the basal crowns and first 20-30cm of rootstock. Total biomass was comprised of the following components: oils, 3.6%; polyphenols, 6.8%; soluble sugars, 6.1%; starch, 1.1% and protein, 7.1%. Lignin and crude fiber were major biomass components. Shoot biomass contained 44.6% lignin and 40.9% crude fiber while root biomass contained 34.2% lignin and 24.6% crude fiber. Seasonal variation in content was evident for all extractives and classes of biomass.

Calorimetric determinations were made for whole plant biomass, extractives and residual biomass. The energy content was as follows: shoot, 4343 cal/g; root, 4214 cal/g and standing dry matter, 4293 cal/g. Whole plant oils had a calorific value of 9513 cal/g with 4976 cal/g for polyphenols and 4228 cal/g in the residue remaining after extraction. Total crop energy yields based on biomass yield and calorific values were 35 to 48 x 10^6 kcal/ha.

It is concluded that E. esula does not presently constitute a productive source of whole plant, extractable oils. Alternative uses of E. esula are not dismissed due to the favorable net energy yield calculated for wild stands of this species. Suggested uses include conversion of whole plant biomass to biocrude oil or a multiple use approach to the use of E. esula biomass as a primary source of lignin

and crude fiber, and secondary raw materials consisting of extractable oils, polyphenols, protein and fermentable carbohydrates.

INTRODUCTION

Euphorbia esula (leafy spurge) is a noxious weed infesting more than 500,000 acres in at least 54 Montana counties (Dunn 1979). The species is endemic to the Caucasus region of Europe and was introduced into North America before 1827 (Croizat 1945; Hanson and Rudd 1933; Selleck et al 1962). Historical accounts of its establishment (Dunn 1979; Britton 1921) and distribution (Hanson and Rudd 1933; Reed and Hughes 1970) indicate a progressive and rapid migration across North America since the early part of the twentieth century. It is classified as a noxious weed in several western states and generally regarded as a serious weed problem (Reed and Hughes 1970). Although most North American material has been identified as Euphorbia esula (Moore 1958 cited in Best et al 1980) there has been some confusion about its identity because of the occurrence of different strains or ecotypes among populations.

Recent accounts of the biology of E. esula have documented the vegetative and reproductive characteristics of this species (Best et al 1980; Morrow 1979). The root system is quite complex, consisting of long and short lateral and horizontal roots (Raju et al 1963) with the vertical roots penetrating the soil to depths of 2.4-9 meters (Bakke 1936; Holmgren 1958). The basal portion of the stem is a perennating structure containing numerous buds and abundant food reserves (Best et al 1980). Stems are typically erect, woody, 30-100cm high and may terminate in an umbellate inflorescence. Phenological aspects of growth and reproduction have been discussed by Selleck et al (1962). Seed production occurs from mid-July until late fall (Selleck 1959).

However, the explosive dehiscence of mature seed capsules in response to high temperature and low humidity (Bakke 1936) would appear to preclude the inclusion of E. esula seed as a source of biomass for possible harvest. The aboveground, living parts of E. esula make up 50 to 57% of the standing crop (i.e., total living biomass) when expressed as a percentage of the total dryweight (Thomas, unpublished - cited in Best et al 1980). Seed and inflorescence make up an additional 8.5% while the remainder of the standing crop (34.5 to 41.5%) is derived from the basal crown and root biomass gathered at harvest.

The establishment of E. esula as a weed in North America is based partly on the virtual absence of endemic predators/pathogens which could serve to retard its successful exploitation of rangeland. Only a few macrophagous insect predators and a rust have been observed to infest E. esula (Harris 1979, cited in Krupinsky and Lorenz 1983). Leaf spot symptoms and reduced seed production occur in plants infected with Alternaria tenuissima, a rust which is endemic to the northern Great Plains (Krupinsky and Lorenz 1983). Limited success in the control of E. esula with Hyles euphorbiae (Spurge Hawkmoth) has been reported (Harris and Alex 1971; Forwood and McCarthy 1980). However, the absence of significant progress to date using biological control agents attests to the adaptability of E. esula as a successful weed.

E. esula has several attributes which mark it as a prospective energy crop: 1) As is typical of members of the Euphorbiaceae, E. esula is a latex producer and thus may serve as a source of natural oils/hydrocarbons. Leaf biomass harvested in southcentral Montana contained 9.3-13.8% oil (Wiatr 1984). Whole plant oil content has been reported to be 4.9% (Hammaker et al 1983), suggesting that stem biomass contains considerably less oil than leaf biomass. Based on a survey of 40 species of prospective oil-bearing species, Hammaker et al (1983) ranked E. esula as a mid-range oil producer. In addition, carbohydrate (78.3%) and total digestible nutrients (96.9%) were considered in the mid-range of levels commonly found in feed. Other species of Euphorbia (E. dentata and E. heterophylla) have been reported to contain hydrocarbons (0.17-0.23%) and oils (6.6-7.9%) and were considered competitive in yield when compared to conventional oil crops (Buchanan et al 1978 a, b).

2) The use of E. esula as a multi-use crop would favor fiber production as well as fermentable carbohydrates which could be converted to ethanol for fuel alcohol production.

3) E. esula would not compete with existing food supplies as is currently a problem with field crops such as wheat and corn which are used as sources of feedstock (starch) for fuel alcohol production. Also, E. esula is not part of the food chain in human nutrition and thus it would not jeopardize the economics or politics of food production. To the contrary, any residual protein obtained after removal of energy feedstocks could be utilized to increase input into the food chain. In oil-depleted meal derived from safflower, sunflower, and rape seed, protein content varied from 28-50% and the suggestion was made that the feed value of the meal could pay for the cost of extracting and processing oil (Peterson et al 1981).

4) The very successful establishment and spread of E. esula in North America, particularly in the northern plains states, suggest that cultivating it as a crop would not require energy-intensive or costly

agronomic practices. The competitive edge demonstrated by the proliferation of *E. esula* and the absence of natural predators in this country would also minimize costs related to pest management.

The current status of most species as renewable energy crops remains equivocal largely because few extensive agronomic studies have been conducted thus far. Oil yields of 5 to 10 barrels per acre were expected from experimental planting of *Euphorbia tirucalli* (Calvin 1979b). *E. lathyris*, an annual, produced 8% to 12% oil estimated to yield 10 to 20 barrels of oil per acre at a cost of $10 to $30 per barrel (Calvin 1979a). Large plots of *E. tirucalli* were subsequently cultivated at the University of California, Davis to determine the influence of irrigation and fertilizer on productivity (Sachs et al 1981). Dry matter and rosin (oil) yields corresponded to 1.3 to 2.5 barrels of oil per acre. Sachs et al (1981) concluded that hydrocarbons from *E. lathyris* would have to sell for $150 to $200 per barrel to be practical as a source of fuel. The attractiveness of *E. lathyris* was further undermined by an extensive three year study at the University of Arizona, Tucson, which seemed to refute earlier claims that *E. lathyris* could be cultivated on arid land (Kingslover 1982). It was concluded that *E. lathyris* had limited value as a crop for liquid fuel production and would not be commercially feasible in the near future based on genetic, agronomic and chemical data. For example, the limited variability in high-energy extractables observed in germplasm of *E. lathyris* collected worldwide indicated that rapid development of improved strains was unlikely. Peterson et al (1981) also concluded that the use of vegetable oil from conventional oilseed crops (sunflower, safflower, winter rape) was economically prohibitive, although improved technology and rapidly rising fuel costs could enhance the economic feasibility of vegetable oils as agricultural fuel.

The objectives of this investigation were to evaluate the productivity of natural stands of *E. esula* in southcentral Montana and to determine the apportionment of biomass with respect to soluble extractives and insoluble materials in both root and shoot biomass. Soluble materials contained oils, polyphenols, hydrocarbons and soluble sugars. Insoluble materials contained starch, lignin, crude fiber and ash. Calorimetric analyses were performed on whole plant biomass and the soluble and insoluble fractions to assess the energy content of these materials and to determine the apportionment of energy in the plant. Energy analyses allowed a basis for comparison of the productivity of *E. esula* with other species and prospective biofuels such as vegetable oils and ethanol.

MATERIALS AND METHODS

Biomass harvests - Biomass samples were harvested from two sites in southcentral Montana, both heavily infested with leafy spurge. The first site, designated Fishtail, was located in Stillwater County approximately 4 miles southwest of the town of Fishtail, Montana and one mile southwest of the point where Fishtail Creek first crosses the county road. The second site, designated Bluewater, was located in Carbon County approximately 3 miles west of the Bluewater fish hatchery near the convergence of the north and south forks of Bluewater Creek. Four harvests at approximately 6 week intervals were made throughout the growing season at each site.

All aboveground biomass was harvested together with 20-30cm of the basal portion of the stem or rootstock. No attempt was made to harvest root biomass deeper than 30cm. The biomass was subdivided into three groups: root, shoot, and standing dry matter. Root and shoot biomass was living material while the standing dry matter was dead shoot biomass from preceding years. All harvested biomass was brought to Eastern Montana College where it was weighed then air-dried (22-27C) to constant weight and reduced in a Wiley mill to pass through a 1mm mesh screen.

Oils, polyphenols, and hydrocarbons - Four to six replicates of comminuted biomass samples, each weighing 15-30g, were sequentially extracted in a Soxhlet apparatus for 24-48h using the method of Buchanan et al (1978a). Acetone extractives were obtained first and these were partitioned between hexanes to extract oils and 87.5%EtOH to extract polyphenols. The residue remaining after acetone extraction was dried in a 55C oven and subsequently extracted with cyclohexane to obtain a hydrocarbon fraction. Initially, the solvents were removed from oils, polyphenols, and hydrocarbons by evaporation in a Buchi rotary evaporator. The residues were then quantitatively transferred to evaporating dishes and allowed to dry further at 40C. Weights were determined gravimetrically and expressed on both a dry and fresh weight basis.

Sugars - Biomass samples (0.5g) for sugar analysis were extracted with 80% ethanol for 24hr at room temperature. Both solvent and sample were then boiled briefly to remove the ethanol. Enough water was added during this step to maintain a volume of approximately 25ml. The solutions were centrifuged at 500g for 10 min to remove the insoluble residue. The supernatant was then decanted and further clarified with neutral lead acetate (AOAC 3.105a in Horwitz 1980). Excess lead was removed by adding solid sodium oxalate crystals until no further cloudiness due to lead oxalate was apparent. Aliquots of this solution were assayed for reducing sugars by the Somogyi titrimetric method (AOAC 3.120 in Horwitz 1980). The neutral lead-free solutions were also assayed for non-reducing sugars. Aliquots were first inverted with 3N HCl for 48hr at room temperature, then neutralized with 2N sodium carbonate. Neutral, inverted solutions were assayed for reducing equivalents as in AOAC 3.120 above. Non-reducing sugar content was the difference in reducing strength expressed in glucose equivalents as determined before and after inversion.

Starch - Starch determinations were made using a modified procedure derived from AOAC 3.120 (Horwitz 1980). Samples of dried biomass (usually 0.5g) were boiled in a small volume of water to gelatinize the starch, after which the starch was solubilized in 30% perchloric acid. Protein in the samples was removed by precipitation with 1.7% uranyl acetate. Solubilized starch in the protein-free samples was precipitated with an iodine-potassium iodide solution in 3% NaCl. After several washings in alcoholic NaCl, the starch-iodine complex which had formed was decomposed with alcoholic NaOH. The liberated starch was washed several times with alcoholic NaCl and subsequently hydrolyzed in 0.7N HCl in a boiling water bath for 2.5 hr. The acid solution was neutralized with NaOH and an aliquot was taken for reducing sugars as above. Known standards of soluble potato starch were used to determine starch content in the biomass samples.

Lignin - The dried residue remaining after acetone and cyclohexane extraction was used for lignin determination following a modification of the indirect-method given in AOAC 3.126 (Horwitz 1980). One gram samples were washed sequentially with ethanol and ether, dried, and digested overnight at 40C in 0.1N HCl contained 1% pepsin. The residue remaining after pepsin digestion was filtered, washed, and refluxed for 1 hr in 5% H_2SO_4. It was then held for 2 hr at 25C in 72% H_2SO_4 and refluxed again for 2 hr in 3% H_2SO_4. The residue remaining after acid digestion was washed and dried at 100C. Lignin content was determined by loss in weight on ignition at 600C.

Crude fiber - Crude fiber content was determined using a modified acid-alkali digestion as given in AOAC 7.068 (Horwitz 1980). One gram samples of oil and hydrocarbon-free residue were sequentially refluxed for 30 min in 1.25% H_2SO_4 and 1.25% NaOH. After a final wash in 1.25% H_2SO_4 and several rinses of boiling water, the residue was dried overnight at 100C. Crude fiber content was determined by loss in weight on ignition at 550C.

Protein - Total nitrogen in biomass was determined by direct Nesslerization of ammonia produced by sulfuric acid and hydrogen peroxide digestion (Dotti and Orten 1971). Nitrogen content was determined colorimetrically and expressed as percent protein using a conversion factor of 6.25 as is used for corn and sorghum (AOAC 14.068 in Horwitz 1980).

Calorimetry - The energy content of whole leaf tissue, extractives and residual biomass was determined with a Parr model 1241 adiabatic oxygen bomb calorimeter. Corrections were made for the heat of formation of nitric acid and heat of compustion of the fuse wire. A thermochemical correction for the heat of formation of sulfuric acid was not included since preliminary analyses indicated that the sulfur content of whole leaf tissues was negligible.

Statistics - Statistical comparisons were made using a modified LSD procedure or Tukey's Honest Significant Difference procedure for multiple comparisons with an SPSS program on a DECsystem 20/60. All comparisons were made at the 5% level of significance.

RESULTS

Biomass yield - Standing crop estimates for this study are derived from biomass harvests conducted in late summer 1982 prior to any significant amount of leaf senescence/abscission which typically occurred during the latter part of September or thereafter. Harvests throughout the growing season indicated that a great deal of phenotypic variability is present in natural populations of *E. esula*, particularly with respect to leaf and stem density. Several individual plants had single stems and roots whereas other, larger units had in excess of 35 stems originating from a single massive crown. Annual increments of growth were evident in transverse sections of the basal crowns suggesting that they were perennial structures which were several years old. No attempt was made to evaluate the influence of these variables on yield.

Standing crop data are given in Table 1. They indicate that a total biomass yield of 3.6 tons per acre (dry weight) was obtained from the Fishtail site and 4.9 tons per acre from the Bluewater site. Shoot biomass was 63.7 to 77.1% of the total biomass present at harvest on a fresh or dry weight basis. To some extent the term "root biomass" as used in this study is a misnomer because it applies to the basal crown of stem tissue and the root/rhizome growing to a depth of approximately 30cm below the surface. This biomass was typically woody and it comprised the balance of the living biomass. As indicated in Table 1, root biomass comprised 24-36% of the dry weight of all living biomass at harvest, with a standing crop yield of 0.89 tons per acre for Fishtail and 1.78 tons per acre for Bluewater.

Biomass apportionment at harvest - Root, shoot and standing dry matter were characterized on the basis of several extractives and solids (Table 2). Extractives included oils, polyphenols, hydrocarbons and total sugars. Solids in the extractive-depleted residue consisted of starch, lignin, crude fiber and ash. It is clear from Table 2 that lignin, and crude fiber together comprised 58% of the root biomass and 85% of the shoot biomass with the percentage of both lignin and crude fiber being greater in shoot biomass. The crude fiber content of standing dry matter ranged between 57.3% and 60.9% for both sites. Lignin determinations were not made for standing dry matter, although it is likely that a large percentage of the extractive and crude fiber depleted-residue consisted of lignin.

Starch content never exceeded 1.8% dry weight and was more abundant in root biomass. Shoot starch content was always less than 1% dry weight. Only trace amounts (0.1% to 0.2%) of starch were found in standing dry matter.

Ash content for root and shoot biomass was approximately 6% with little variation between shoot and root. Standing dry matter contained 3.0-3.2% ash or about one-half the ash content of root or shoot.

Collectively, all extractives comprised 14.6% to 18.5% of the total living biomass present at harvest. Hydrocarbons rarely exceeded 0.1% and were usually found in trace amounts. Root biomass contained 2.6% to 3.8% oil while shoot biomass oil content was slightly greater (3.4% to 4.1%). Standing dry matter from previous years' growth had 1.0% to 1.4% oil which indicated that not all oils are leached immediately at the end of the growing season. Polyphenol content ranged between 5.2% and 7.5% for root and shoot biomass and thus comprised a noteworthy extractive in living biomass. Soluble (total) sugars also comprised a major class of extractives in both root and shoot biomass and was greatest (8.5%) in roots harvested at the Bluewater site. Polyphenols and sugars were not significant components of standing dry matter. The highest contents of polyphenols and sugars were obtained from standing dry matter at the Bluewater site and these were 1.2% and 0.3%, respectively.

Protein - Modified Kjeldahl nitrogen determinations were done for root, shoot, and standing dry matter collected during the September harvest at both Bluewater and Fishtail. Protein content was calculated from the nitrogen data using a conversion factor of 6.25, a value used to calculate protein content in corn and sorghum (Horwitz 1980). The results in Table 6 indicate that shoot and root biomass have comparable levels of protein with a mean value of 7.2% (range 6.50 to 7.88%). Standing dry matter had considerably less protein (3.3%) than shoot or root biomass.

Seasonal variation in biomass apportionment - It was of interest in this study to evaluate the extent to which seasonal variation occurred in the apportionment of extractives and residual biomass in *E. esula*. The rationale for this approach is based on the premise that periodic harvests throughout the growing season rather than a single harvest at the end might produce a greater total yield of useful raw materials. The results are given in Figures 1-6.

Oils - In Fig. 1 it is evident that a late summer drop in oil content occurred in both root and shoot biomass. In early July (harvest of 7/7/82) oil content ranged from 4% to 5.5% for all biomass. Two months later (harvest of 9/6/82), however, a significant decrease in oil content occurred, resulting in a lower range of 2.5% to 4.0%. The subsequent pattern of oil content in spurge biomass was evidently site dependent. The oil content of biomass harvested in October at the Fishtail site indicated a further decline to seasonal lows of 3.2% for root biomass and 3.7% for shoot biomass. In contrast the oil content of all biomass at the Bluewater site underwent a sharp increase in oil content to levels which exceeded those of the first harvest in early July. Thus in addition to seasonal fluctuations occurring in oil content, population or site-specific differences may cause oil content variations.

Polyphenols - As Fig. 2 indicates, seasonal fluctuations were also observed in the polyphenol content of spurge biomass. A decline in polyphenols occurred during the first eight weeks of the growing season (May 15-July 7) in shoot biomass harvested from the Fishtail site. An increase in polyphenol content occurred in all biomass at both sites between July and September. For example, polyphenol content increased from 2% to 5% in shoot biomass at the Bluewater site.

The polyphenol content of biomass harvested in October increased, decreased or remained unchanged, depending on the type of biomass considered and the harvest site. Shoot biomass at the Fishtail site had a significantly lower polyphenol content whereas Bluewater shoot biomass harvested at the same time had a significant increase. Root biomass from the Fishtail site had a significant increase in polyphenol content while polyphenols in root biomass from the Bluewater site remained unchanged.

Sugars - Seasonal changes in total sugar content are given in Fig. 3. Following the July harvest, both shoot and root biomass underwent a progressive increase in total sugar content. A late harvest (October) favored maximum sugar content in root or shoot biomass at both sites. Throughout the growing season, root sugar content was approximately twofold greater than shoot sugars.

Starch - Seasonal changes in shoot and root starch levels are given in Fig. 4. Throughout the growing season, shoot starch never exceeded 0.5% and always remained less than root starch content. Maximum root starch (1.6% to 1.8%) was observed in the September harvest for both sites. Root biomass harvested in October had approximately 30% less starch and thus gave yields between 1.1% and 1.3%.

Lignin - Lignin remained a relatively abundant component of spurge biomass throughout the growing season (Fig. 5). The ranges of lignin content at both sites were 26.8% to 46.1% for shoot biomass and 33.9% to 45.9% for root biomass. An initial increase in lignin content was evident during the first several weeks of the growing season for root biomass from the Bluewater site and shoot biomass from the Fishtail site. Later (July-September) the lignin content of root biomass decreased at both sites but was subsequently followed by a small but significant increase for the remainder of the season. Conversely, shoot lignin content increased between July and September but declined through October.

Crude fiber - Seasonal changes in crude fiber levels are given in Fig. 6. At both sites, root crude fiber content declined from July to September. A particularly large drop from a seasonal high of 41.5% to a seasonal low of 24.7% was evident in root biomass harvested at the Fishtail site. However, most crude fiber yields ranged between 35% and

45% of the total biomass expressed as a percentage of the total dry weight. Root crude fiber content was approximately 38% at both sites in October, indicating that an increase in root crude fiber content occurred during the latter part of the growing season. An increase in crude fiber was observed between July and September in shoot biomass at both sites, although subsequent levels appeared to be site specific. Shoot crude fiber content decreased in biomass harvested from the Fishtail site while no significant change was observed at the Bluewater site.

Absolute yield of apportioned biomass - Yield and composition data from the September harvest were used to calculate absolute yields of extractives and solids. Yield data derived from natural stands of vegetation in this way are not necessarily an accurate measure of productivity because routine agronomic practices (irrigation, fertilization, etc.) increase crop productivity. The absolute yield data given herein are interpreted as an indication of the minimum yield which could be achieved with *E. esula* at present.

Oils - Values given in Table 3 indicate that total oil yield was not greater than the equivalent of one barrel per acre from all living biomass harvested at either site. Shoot biomass yielded 140 lbs. (0.5 barrel) per acre from Fishtail and 212 lbs. (0.7 barrel) per acre from Bluewater. Oil yield from root biomass was approximately one-half the oil yield of shoot biomass, thus contributing an additional 58 lbs. to 93 lbs. per acre to the total oil yield. The mean oil yield for both Bluewater and Fishtail was 260 lbs. (0.9 barrel) per acre.

Polyphenols - Polyphenol yield was 592 lbs. per acre for Bluewater and 372 lbs. per acre for Fishtail. As with oils, shoot polyphenol yield exceeded root yield for both sites. Shoot polyphenols comprised 54.9% of the total polyphenol yield at Bluewater and 64.2% at Fishtail. Thus the contribution of polyphenols solely from shoot biomass would be approximately 282 lbs. per acre.

Total sugars - Sugar yields for all biomass from both sites was of the same order of magnitude as polyphenols, with a mean total yield of 468 lbs. per acre. Bluewater biomass had the greatest sugar yield of 553 lbs. per acre, and this was divided between shoot and root biomass in a ratio which approximated 1:2. Thus although root biomass comprised only 36.3% of the total biomass at harvest (Table 1), the higher sugar content of root biomass (8.8% vs. 4.0% for shoots) resulted in a twofold greater sugar yield from root biomass. Fishtail shoot and root biomass produced a total yield of 383 lbs. per acre. The mean yield from both sites indicated that roughly equivalent amounts of sugar were produced by root and shoot biomass. The mean total sugar yield for both sites was 468 lbs. per acre.

Starch - Starch comprised a relatively minor biomass component in *E. esula*. Root biomass harvested from Bluewater produced the largest quantity of starch (57 lbs. per acre). Total starch yield (88 lbs. per acre) was also greatest from Bluewater since shoot biomass contributed an additional 31 lbs. per acre, an amount which was approximately 49% of the starch yield from Bluewater. The mean total starch yield from both sites and all biomass was 66 lbs. per acre.

Lignin and crude fiber - Lignin and crude fiber yield exceeded the collective yield of all other biomass constituents. The mean total yield of lignin and crude fiber was 5714 lbs. per acre with lignin comprising 54% of the total. The mean lignin yield from shoot and root biomass was 3084 lbs. per acre. Shoot lignin yield was 2.3 to 2.6 times greater than root yield, and thus comprised 69-72% of the total lignin at harvest. The total crude fiber yield was 1978 lbs. per acre for Fishtail and 3281 lbs. per acre for Bluewater. Shoot crude fiber yield was 2.8 to 3.5 times greater than root yield, and thus comprised 73-78% of the total crude fiber at harvest.

Energy content - Calorific values were determined for shoot biomass, root biomass, standing dry matter and partitioned biomass consisting of oils, polyphenols and the residue remaining after extraction. Sugars, starch, lignin and crude fiber in the residual biomass were not separated prior to calorimetric determinations. As indicated earlier, the residual biomass consisted largely of equal amounts of lignin and crude fiber.

Calorific values are given in Table 4. The range of calorific values for all biomass/extractives was 4214 to 9522 cal/g. All whole plant biomass (root, shoot and standing dry matter) had calorific values less than 5000 cal/g. The lowest calorific value was obtained from root biomass (4214 cal/g) while shoot biomass had a slightly but significantly higher energy content of 4344 cal/g. The energy content of polyphenol and oil depleted residual biomass (4217 cal/g) was statistically equivalent to root biomass (4214 cal/g) and was somewhat greater than whole plant biomass. Oils had the highest energy content (9522 cal/g) with values from all samples in excess of 9000 cal/g.

Energy yield - Standing crop data from the September harvest (Tables 1 and 2) and calorific values (Table 4) were used to calculate total and apportioned energy yields on a per acre basis. As Table 5 indicates, the total (net) energy yield from the September harvest of

E. esula was 14.15 x 10^6 kcal per acre for Fishtail and 19.36 x 10^6 kcal per acre for Bluewater. The mean energy yield for all biomass (except standing dry matter) from both sites was 16.76 x 10^6 kcal per acre, with shoot biomass yielding twice the energy of root biomass. The greater energy yield from shoot biomass is largely related to its greater mass yield since the calorific values of shoot and root biomass did not differ greatly (Tables 1 and 4).

Apportioned energy yields for oils, polyphenols and residual biomass are also given in Table 5. The mean energy yield for oils was 1.28 x 10^6 kcal per acre. This value represents 7.6% of the total energy yield at harvest. Energy yield data for shoot and root oils indicated that shoot oil energy yield was 2.3 to 3.3 times greater than root oil energy yield. Polyphenols yielded 1.18 x 10^6 kcal per acre, and this value represented an additional 7.1% of the total energy yield at harvest. Shoot polyphenol energy yield was 36% greater than root yield at Fishtail and 60% greater at Bluewater. The energy values for residual biomass in Table 5 clearly indicate that this class of biomass represents the single, largest energy component of E. esula biomass. The mean energy yield for residual biomass was 14.30 x 10^6 kcal per acre, and this value represented 85.3% of the total biomass energy at harvest. The energy associated with residual biomass was derived mostly from shoot biomass (64.0-75.1%) because of its greater mass yield. As noted earlier, the comparatively high percentage of crude fiber and lignin in residual biomass would indicate that a large percentage of the residual biomass energy is derived from these constituents. It is noteworthy, too, that the energy yield of residual biomass was 5.8 times greater than the combined energy yield of oils and polyphenols.

DISCUSSION

Buchanan et al (1978a) suggested that one goal of renewable energy research should be the development of a crop in the United States as productive of oils and hydrocarbons as Hevea, the rubber tree, which produces 2000 lbs per acre of natural rubber in Southeast Asia. As an example of the increase in productivity which must be met to attain this goal, yield and economic return data were cited for two species of domestic, wild rubber-bearing plants (Apocynum cannabinum and Ascepias syriaca). These data indicated that a twofold increase in oil content and a twofold increase in biomass would be needed to make these species as productive as Hevea.

The yield data for E. esula in this study (Table 1) are based strictly on biomass harvested from natural stands which have not been subjected to any agronomic practices. These data should therefore be interpreted as a conservative indication of the biomass potential of E. esula where limiting environmental factors constrain productivity. Oil content and biomass yield data suggest that an eightfold increase in oil content or an eightfold increase in biomass yield or a combination of these two parameters would be needed to achieve an oil yield competitive with natural rubber.

Two thousand lbs of oil per acre would be produced by E. esula if the biomass evaluated in this study had an oil content of 30.4%, which represents an eightfold increase over the oil content of existing stands of this plant. As indicated in Table 8, the oil content of whole plant biomass derived from several species in the genus Euphorbia seldom exceeded 10%. Although leaves of E. esula contain more oils than shoot biomass (Table 8), the total oil yield is reduced by the low oil content of stem biomass. In 15 species screened for whole plant oils, the highest oil content reported was 9.68% for Euphorbia dentata (Buchanan et al 1978b). The highest whole plant oil content from 16 potential oil species in Montana was 13.1% reported for Grindelia squarrosa (Hammaker et al 1983). These oil yield data from a broad sampling of unrelated species suggest that the attainment of 30.4% oil from whole plant biomass is unrealistic.

A fourfold increase in whole plant biomass yield would require only a twofold increase in oil content (to 7.6%) in order to approach a yield of 2000 lbs per acre. An oil content of 7.6% in whole plant biomass is plausible since numerous species have already been identified with oil in excess of 6% (see Table 8). Thus an oil content of 7.6% does not appear to be a physiologically determined upper limit for whole plant biomass. Historically, important food crops such as rice and wheat have undergone at least fourfold increases in productivity (Wallace and Zobel 1982). Corn yield in 1935 averaged 80 bushels per acre in contrast to recently developed hybrid varieties which yield about 140 bushels per acre (Wallace and Zobel 1982). Dry matter production in Euphorbia lathyris was directly related to irrigation (Sachs et al 1981). Plants receiving no irrigation produced 3.1 to 4.6 tons per acre whereas irrigation with 66 cm of water increased yield to 7.3 to 8.6 tons per acre. Thus it is reasonable to expect significant increases in dry matter production in E. esula through genetic selection and agronomic practices that would be selective for enhanced dry matter production and oil content.

The extent of ecotypic variation and the influence of numerous agronomic parameters have been investigated in a comprehensive three year study of the biofuel potential of Euphorbia lathyris (Kingslover 1982). Apart from the close genetic relationship between E. lathyris and E. esula, this study serves to identify many of the significant parameters that could influence the productivity of E. esula if adopted as a crop plant. For this reason, a discussion of some of the salient observations reported in Kingslover's (1982) study follows.

Ecotypic variation and agronomic parameters (field water use, plant density, fertilizer effects, and mycorhizae) were investigated as related to the enhancement of oil content or biomass yield. Variance in extractables from a world collection of germplasm did not differ greatly from variance in a relatively homogeneous stock of germplasm from a specific ecotype of E. lathyris. The low degree of variance in oil content attributable to genetic differences suggested that plant breeding to increase oil content in the near future would be difficult or impossible. The range of extractables (oils) from the world collection of germplasm was 4.25% to 13.25% (mean 8.17%) for field grown material. The observation that genetically homogeneous plants had a comparable range (4.75% to 13.25%) suggested that physical parameters (plant density, phenology, climate) were of greater importance to oil content than genetic variability. In this study, variability in oil content was clearly observed between the two populations sampled concurrently at various times throughout the growing season and between shoot and root biomass. The extent to which the variability in oil content in E. esula is genetic or environmentally influenced was not determined. However, the implication from Kingslover's (1982) study is that oil content in

Euphorbia is strongly regulated by environmental parameters much more than inherent genetic variability.

Although E. lathyris had been perceived as a xerophytic plant well adapted to arid lands, water use data given by Kingslover (1982) indicated a water requirement greater than that of spring and fall grains (wheat and barley). It is noteworthy, however, that the water requirement for E. lathyris (101 cm) was significantly less than alfalfa (197 cm).

A positive correlation was observed between high density planting and total dry matter production in the Kingslover study. A higher yield of extractables was obtained with larger biomass yields, but high density plantings also favored a greater stem:leaf ratio. Since leaves of E. lathyris have a higher oil content than stems (Sachs et al 1981) the value of high density plantings to obtain high biomass yields may be questionable. Leaves of E. esula contain a relatively high percentage of oil (Wiatr 1984). Using leaves of E. esula to study the influence of dehydration on yield, Wiatr (1984) reported leaf oil yields of 9.3% to 13.8%. In this study, oil content for shoot (stems and leaves) biomass never exceeded 5.4%, indicating that stem biomass in E. esula has a dilutive effect on total oil yields similar to E. lathyris. It is evident that increased oil yield could be achieved through ecotype selection and agronomic practices which favor a high leaf:stem ratio to optimize leaf biomass rather than total biomass yield.

Fertilization and mycorhizal fungi may also enhance productivity of E. esula. Seedlings of E. lathyris responded favorably to fertilization with phosphorus and nitrogen (Kingslover 1982). Plants of E. lathyris infected with mycorhizal fungi (Glomus trappei or Glomus mosseae) achieved a four to fivefold increase in fresh biomass, an increase attributed largely to enhanced uptake of phosphorus and other essential nutrients (Kingslover 1982).

Oil content and yield - A large base of comparative data has been generated on oil content in wild species having potential as whole plant or seed oil crops (Barclay and Earle 1974; Buchanan et al 1978a, b; Buehrer and Benson 1945; Hall and Goodspeed 1919; Hammaker et al 1983; Minshal N.A.; McLaughlin and Hoffman 1982; Princeton 1979). Members of the Euphorbiaceae have often been included in such surveys since latex commonly occurs in this family. A summary of oil content and other data for several species in the Euphorbiaceae is given in Table 7. These data collectively indicate that oil content can vary substantially, depending on the species and type of biomass evaluated (e.g., shoots or leaves). No reports were found on oil content in root biomass in E. esula.

The oil content reported for E. esula in this study is consistent with that reported for E. esula shoot biomass by Hammaker et al (1983). The range of oil content for E. esula biomass (shoot or root), including seasonal variation, is also within the range of values given in Table 7. Judging from Wiatr's (1984) (and see Table 7) report on oil content in leaves of E. esula, it is evident that leaf biomass contains a higher oil content than stem biomass. A similar observation has been reported for oil content in leaves and stems of Euphorbia lathyris (Sachs et al 1981).

In a recent regional study, Hammaker et al (1983) examined prospective whole plant oil species for Montana derived largely from an inventory of approximately 700 species developed by Roth et al (1982) and McLaughlin and Hoffman (1982). Represented in the study were 7 families and 18 species having oil contents which ranged from 1.7% (Carduus nutans) to 13.1% (Grindelia squarrosa). The two species of Euphorbia examined, E. esula and E. marginata, had oil contents of 4.9% and 4.7%, respectively. Based on oil content, E. esula was initially placed in a medium priority grouping, but later lowered in priority ranking due to potential eradication problems. The results of this investigation indicate that, despite variation in oil content due to seasonal fluctuation and biomass (root vs. shoot), E. esula would be appropriately ranked with other species of medium priority based solely on oil content.

Relationship between oil content and oil yield - Oil content (i.e., percent oil) data give a useful initial assessment of the oil producing potential in plant biomass. However, yield data must be used in conjunction with content data in order to accurately assess the oil potential of a species. A graph illustrating the general relationship between biomass yield and extractive content is given in Figure 14. For example, an oil extractive yield of 200 pounds per acre could be achieved from a species with 10% extractive and one ton of biomass per acre. The same extractive yield could also be achieved from a species with 5% oil producing two tons of biomass per acre. Figure 14 is meant to depict an ideal relationship between content and yield since studies have demonstrated that oil content decreases as biomass yield increases (Sachs 1980; Kingslover 1982). Nevertheless, Figure 7 is instructive because it indicates in general terms the relationship between biomass yield and extractive content.

Figure 15 is a duplication of Figure 14 with additional information derived from oil content and yield data for selected plant species. The vertical bar labelled "whole plant oil" indicates the range of oil content for species investigated by Buchanan et al (1978a,b) and Hammaker (1983). The upper limit of the vertical bar corresponds to an oil content of 14%. (The position of the vertical bars in relation to the abscissa is irrelevant.) Only one species, Grindelia squarrosa, investigated by Hammaker et al (1983) had a whole plant oil content greater than 11%. The range for all other species was 1.9% to 10.7% with a mean of 5.2%. The value of approximately 14% is important because it represents the upper limit of the whole plant oil content for wild plant species in Montana and, in all likelihood, in North America as well.

The other vertical bars in Figure 15 labelled seed oil indicate the range of oil content for wild and cultivated oil-bearing seed plants using data from Hammaker et al (1983). The narrower range and higher oil content of cultivated oil seed plants such as sunflower and flax demonstrate the influence of artificial selection for high oil cultivars. Thus the upper limit for seed oil content in cultivated plants (45%) is somewhat greater than the upper limit for wild plants (36%). Also, the upper limit of the oil content in seed biomass is characteristically higher than the upper limit of the oil content in whole plant biomass.

Known combinations of biomass yield and oil content have been used in Figure 15 to generate yield envelopes which circumscribe the range of oil production for a given species. Where actual oil yields are known, the envelope has been truncated further to delimit the range over which biomass yield or oil content govern yield. As indicated in Figure 15, oil seed crops such as sunflower and safflower are near the upper limit of oil content in cultivated seed crops. Thus increased oil production in these species could best be achieved through increased crop (seed) yields.

Productivity data obtained from Kingslover (1982) have been used to construct a yield envelope for whole plant biomass of E. lathyris. The envelope demonstrates that oil yields comparable to cultivated seed oil crops can be achieved with E. lathyris since higher biomass yields compensate for lower oil content. Because the oil content reported for E. lathyris approaches the upper limit for whole plant biomass, increased oil yield in this species could be achieved largely if not solely by an increase in biomass yield. As discussed by Kingslover (1982), however, oil content in E. lathyris decreases somewhat with increased biomass yield, thus making further increases in oil yield difficult to achieve.

It is possible now to give a preliminary evaluation of E. esula as an oil crop in the context of those species already discussed. The oil yield envelope constructed for E. esula is based on standing crop and oil content data derived from wild populations investigated in this study. The position and dimensions of the envelope suggest that E. esula would not presently be an attractive whole plant oil crop compared to cultivated oil seed crops. The position of the envelope also suggests that oil content is well below the upper limit for whole plant biomass. Selection of strains of E. esula high in oil content would favor oil yields which would approach but not exceed oil yield currently obtained from conventional oil seed crops. Cultivation of

E. esula with conventional agronomic practices may favor increased biomass yield. Such a combination of both biomass yield and oil content would be necessary before E. esula could be competitive with oil seed crops presently cultivated in Montana.

Polyphenols - The polyphenol content obtained for E. esula biomass in this study is comparable to that obtained for other Euphorbia species (see Tables 2 and 8). Roots would be a somewhat richer source of polyphenols due to their slightly higher polyphenol content, whereas standing dry matter constitutes a negligible source of polyphenols. Yield data in Table 3 and content data in Table 2 indicate that polyphenols exceeded both oil content and yield and thus would comprise an important class of extractives obtained from E. esula biomass.

A problem with polyphenols may be related to end use rather than yield. The polyphenol fraction isolated from plant biomass is a rather broad spectrum of phenolic compounds, tannins and complex lipids (Buchanan et al 1978b). The heterogeneity of this fraction and its comparatively low energy content (Table 4) suggest that this fraction could serve better as a source of industrial raw materials for specialty chemicals rather than as an energy source.

Crude fiber and lignin - The high crude fiber and lignin content of E. esula biomass warrant serious consideration regarding the use of these materials in order to enhance the economic attractiveness of E. esula as a renewable energy crop. Conversion technologies being investigated suggest that a variety of end uses could be obtained from both crude fiber and lignin. Whole plant biomass conversions include thermochemical liquefaction into oil for fuel or chemical feedstocks (Elliot 1981), small scale combustion, gasification or pyrolysis with fluidized bed systems (Soltes et al 1982) and microbial suppressed methane production coupled with electrolysis of high molecular weight organic acids to produce liquid fuel or industrial chemicals (Levy et al 1981). This latter system is noteworthy since a favorable energy balance was suggested.

The phenylpropanoid skeletal structure of lignin makes it well suited for the production of valuable phenolic compounds (Goldstein 1975; Crawford 1981). Microbial conversion of lignin to low molecular weight phenolics has been reported using Streptomyces viridosporus, a lignocellulose decomposing actinomycete, and Coriolus versicolor, a white-rot fungus (Crawford 1981). By-products derived from degraded lignin include polymers, modified polymers, pre-polymers, low molecular weight specialty chemicals and fuels (Sundstrom and Klei 1982). Emphasis in this latter study was placed on the large scale use of biomass lignins as plywood adhesives and asphalt extenders since both applications would be competitive with the present use of waste lignin as a fuel to power solvent recovery processes in pulp mills. Lignocellulosic fractionation processes and applications also have been discussed (Lipinsky 1981).

Fermentable carbohydrates - Yields for total (soluble) sugars and starch (Table 3) have been summed and expressed as fermentable carbohydrates in Table 11. Soluble sugars comprised 86% to 90% of the total fermentable carbohydrates in biomass, indicating that starch is not a significant component of fermentable carbohydrates. Carbohydrate yields for a limited sampling of cereal grains grown in Montana are given in Table 10. The mean carbohydrate yield for all biomass was 484 lbs per acre. Compared to cereal grain yields in

Table 9, this value is 51.3% of the carbohydrate yields obtained for barley, 44.1% of that for wheat, and 14.4% of that for corn. Thus fermentable carbohydrate yield in E. esula is well below mean yields for cereal grains commonly grown in Montana. Nevertheless, fermentable carbohydrates, particularly soluble sugars, represent a significant component of E. esula biomass.

Protein - Protein derived from oilseed meal may have important feed value as a supplement to swine, poultry or ruminant rations although in some cases oilseed protein has not been entirely acceptable due to an absence of lysine (an essential amino acid) or because of high fiber content or the presence of toxic compounds (Peterson et al 1981). In contrast to oilseed meal, protein levels in whole plant biomass are typically lower, ranging from 7.6% to 22.1% (Table 9). Protein levels for forage crops compare to those recorded for whole plant biomass.

Protein levels given for E. esula in this study agree with values reported by Hammaker et al (1983) (and see Table 9). Based on the forage crop values given in Table 9, Hammaker et al (1983) ranked E. esula's protein content just below the mid-range found in Montana feedstuffs. As indicated in Table 6, root protein in E. esula could be ranked similarly whereas the protein level in standing dry matter is low.

The moderate feed value of E. esula biomass as a source of protein for livestock is diminished by the well documented occurrence of skin irritants and cocarcinogens in latex from the genus Euphorbia (Upadhyay et al 1980; Furstenberger and Hecker 1977; Adolf and Hecker 1971; Sofat et al 1972). E. esula sap has been found to cause loss of hair on horses' feet (Muenscher 1935, 1960) and dermatitis in humans (Johnson and Smoliak 1965). Ingestion of E. esula hay by livestock does not seem to cause death (Holmgren 1958) although it has been found to cause scours and weakness in cattle (Muenscher 1960). Equally well documented, however, is the ability for sheep to graze on E. esula biomass and tolerate toxins (Muenscher 1930; Christensen et al 1983; Helgeson and Thompson 1939; Johnson and Peake 1960). Since the reports cited center on the problems associated with latex contained in whole plant biomass, it is conceivable that extraction of oils and soluble carbohydrates also would remove oil or water soluble toxins and thus enhance the value of the residue as an enriched protein supplement for livestock.

Calorific values of biomass - The calorific values reported in this study for whole plant biomass, extractives and residual biomass are in general agreement with previously reported values for biomass derived from other species (see Table 13 for a list of calorific values). E. esula shoot and root biomass had lower gross heat values than leaf biomass reported recently by Wiatr (1984). This could be attributed to the lower oil content of root and shoot biomass since the gross calorific value of whole plant biomass also would be lowered.

Polyphenol energy values reported in this study fall within the range of values reported for polyphenols (Table 13). The mean calorific value for polyphenols (4976 cal/g) is somewhat greater than the value for whole plant biomass. Nevertheless polyphenols comprise an energy poor class of materials which appear to be oxidized at a level comparable in energy yield to wheat straw and wood as given in Table 13.

Oil energy values for E. esula agree with those reported by Wiatr (1984) for oils extracted from leaf biomass of E. esula. The oil energy values are also comparable to values reported for hexane extractables from leaves of Calotropis procera (Erdman and Erdman 1981), "hydrocarbons" (oils) from Euphrobia lathyris (Nementhy et al 1979) and vegetable seed oils (Peterson et al 1981). Calorific values for E. esula oils were considerably greater than lignite or anthracite coal, but less than petroleum (crude oil), fuel oil and diesel fuel (Table 13).

Because residual biomass is a heterogeneous material comprised mostly of soluble sugars, crude fiber and lignin, the energy value reported for this material is a composite value, but derived largely from crude fiber and lignin, the principal constituents. As indicated by its calorific value, residual biomass is comparable to whole plant biomass energy values. This is not unexpected since residual biomass (including sugars) comprised 66.5% to 90% of the total organic matter. The energy value of lignin has been reported as 6306 calories per gram (Sundstrom and Klei 1982). Using this energy value for the lignin fraction of residual biomass, the crude fiber component would have a calculated gross energy value of 2183 calories per gram in shoot and 2030 calories per gram in root biomass. These energy values are quite low and suggest that the crude fiber fraction is a very low energy component of biomass.

Net energy yield - Net energy yield per unit area for a given species allows useful comparisons of efficiency based on the storage of photosynthetically reduced carbon in plant biomass. The inherent difficulty associated with crop evaluation strictly on the basis of economic potential warranted this approach in order to compare _E. esula_ with crop plants currently grown in Montana. Using net energy yield per unit area is further justified since the energy potential of _E. esula_ is of primary interest and, in principal, all harvested plant biomass constitutes crop yield.

Examples of net energy yield per unit area of cropland are given in Table 12 for Montana crops. As these values indicate, the range of total net energy values is 19.64 to 43.16 x 10^6 kcal/ha for four crops. Winter wheat and barley have the lowest net energy values (19 to 28 x 10^6 kcal/ha), corn the next highest (23 to 28 x 10^6 kcal/ha) and sugar beets the highest energy yield of all crops listed in Table 12 (41 to 43 x 10^6 kcal/ha). Based on the values in Table 12, wheat/barley, corn and sugar beets are ranked as low, medium and high energy-yielding crops.

Net energy yield values for _E. esula_ are given in Table 6. A comparison of these data with values for conventional crops given in Table 12 indicates that net energy yield in _E. esula_ is comparable to the net energy yield of sugar beets grown in Montana. The implication, therefore, is that wild stands of _E. esula_ constitute a high energy yielding species. This preliminary conclusion, however, is neither accurate nor entirely valid since sugar beet energy yield data are based on annual growth whereas biomass fixed in previous seasons contributed to the standing crop and thus energy yield of _E. esula_. The relationship between annual productivity and standing crop (total productivity) in _E. esula_ is not known and this area must be investigated further to more accurately assess _E. esula_'s energy potential in relation to conventional crops.

Energy values for crop yield and residual biomass in Table 12 indicate that energy apportionment varies considerably among crop plants. In beets, for example, approximately 81% of the net energy is present in the root system. In contrast, cereal grains have 27-50% of the net energy allocated to crop biomass (i.e., grain). In *E. esula*, approximately 68% of the net energy yield is contained in shoot biomass (Table 5). Of the total energy in shoot biomass, 8.2% is derived from oils and 6.0% is from polyphenols (Table 5). The bulk of the energy in shoot biomass (85.9%) is in the form of residual biomass consisting mostly of crude fiber and lignin. In root biomass of *E. esula*, more energy is obtained from polyphenols than oils (9.4% vs. 6.5%), while residual biomass again gave the largest energy yield (84.1%).

CONCLUSIONS

The use of wild stands of E. esula strictly as an oil-producing crop is not justified at present due to the medium oil content of whole plant biomass and preliminary yield data which indicate that total oil yield would not exceed one barrel per acre. The attractiveness of this species as an oil producer could be enhanced specifically through agronomic practices favoring increased biomass production and a selection program for high oil content as well as a high leaf:stem ratio.

Despite low oil yield, energy yield data for E. esula indicate that this species is an attractive net energy producer. Thus, the use of whole plant biomass as a source of biofuel is favored over simple extraction of whole plant oils. It is suggested that subsequent conversion of whole plant biomass into biocrude oil or direct utilization by combustion should be investigated.

An alternative approach to the utilization of E. esula should be to regard this species as a multiple-use crop. Perceived in this way, E. esula would primarily be a source of lignin and crude fiber for use in conversions not necessarily related to energy production. Oils, polyphenols, fermentable carbohydrates and protein-enriched residues would be by-products of secondary importance. These secondary materials would presumably contribute to a favorable energy balance if E. esula were to be harvested and processed as a multiple-use crop.

TABLE 1: STANDING CROP*

Yield (tons/acre)
()=% of total

	ROOT		SHOOT		TOTAL	
	Fresh	Dry	Fresh	Dry	Fresh	Dry
Fishtail	1.78(22.1)	0.89(24.9)	6.65(77.1)	2.68(75.1)	8.08	3.57
Bluewater	3.57(30.8)	1.78(36.3)	8.03(69.2)	3.12(63.7)	11.60	4.91

* harvest date 9/6/82

TABLE 2: BIOMASS COMPOSITION*

CONTENT (% Dry Weight)

		EXTRACTIVES				SOLIDS				
Site	Biomass Type	Oils	Polyphenols	Hydrocarbons	Total Sugars	Starch	Lignin	Crude Fiber	Ash	Misc.
Bluewater	Shoot	3.4	5.2	0.1	4.0	0.5	43.8	38.6	5.9	-
	Root	2.6	7.5	0.1	8.5	1.6	33.9	24.5	5.8	15.5
	Standing Dry Matter	1.4	1.2	<0.1	0.3	0.2	-	57.3	3.0	36.5
Fishtail	Shoot	4.1	6.7	0.5	4.9	-	45.3	43.2	5.9	-
	Root	3.8	7.5	<0.1	6.8	1.8	34.5	24.7	6.6	14.2
	Standing Dry Matter	1.0	0.7	<0.1	<0.1	0.1	-	60.9	3.2	33.8
Mean for Two Sites	Shoot	3.8	6.0	0.3	4.5	0.5	44.6	40.9	5.9	-
	Root	3.2	7.5	0.1	7.7	1.7	34.2	24.6	6.2	14.9
	Standing Dry Matter	1.2	1.0	<0.1	0.2	0.2	-	59.1	3.1	35.2

* harvest date 9/6/82

TABLE 3: YIELD OF APPORTIONED BIOMASS*

Yield (lb/acre)

		EXTRACTIVES		SOLIDS					
Harvest Date & Site	Biomass	Oils(*)	Polyphenols	Total Sugars	Starch	Lignin	Crude Fiber	Ash	Misc.
Bluewater	Shoot	212(0.7)	325	250	31	2733	2409	368	6
	Root	93(0.3)	267	303	57	1207	872	207	555
	TOTAL	305(1.0)	592	553	88	3940	3281	575	562
Fishtail	Shoot	146(0.5)	239	262	11	1613	1538	210	-
	Root	68(0.2)	134	121	32	614	440	118	225
	TOTAL	214(0.7)	372	383	43	2227	1978	328	225
Mean for Both Sites	Shoot	179(0.6)	282	256	21	2173	1274	289	-
	Root	81(0.3)	201	212	45	911	656	163	390
	TOTAL	260(0.9)	482	468	66	3084	2630	452	390

* harvest date 9/6/82

TABLE 4: CALORIFIC VALUES

Energy (cal/g)

		Whole Plant			Extractive		
Site	Harvest Date	Shoot	Root	Standing Dry Matter	Oils	Polyphenols	Residual Biomass
Fishtail	9/6/82	4462	4274	4278	9666	5076	4317
	10/10/82	4343	4293	----	9533	4949	----
Bluewater	9/6/82	4257	4177	4287	9374	5076	4139
	10/10/82	4308	4111	4341	9477	4803	----
Mean - All Harvest		4343	4214	4293	9513	4976	4228
Standard error		(40.9)	(22.5)	(10.4)	(39.0)	(70.5)	(45.2)

TABLE 5: ENERGY YIELD BY BIOMASS TYPE AND EXTRACTIVE

	Energy($x10^6$ kcal/ha)*			
Biomass	Oils	Polyphenols	Residue	Total
Bluewater Site				
Shoot	2.23	1.85	26.42	30.50
Root	0.97	1.52	14.85	17.34
Total	3.20	3.37	41.28	47.84
Fishtail Site				
Shoot	2.38	1.52	22.06	25.96
Root	0.73	0.95	7.32	9.01
Total	3.11	2.48	29.38	34.97
Mean for Both Sites				
Shoot	2.31	1.69	24.24	28.23
Root	0.85	1.24	11.08	13.17
Total	3.16	2.92	35.33	41.41

* Hydrocarbons omitted due to negligible yield

TABLE 6: NET ENERGY YIELD FOR *E. esula*.

	Net Energy Yield ($x10^6$ kcal/ha)		
Site	Shoot	Root	Total
Bluewater	20.50	17.34	47.84
Fishtail	25.96	9.01	34.97
Mean for Both Sites	28.23	13.17	41.41

TABLE 7: PROTEIN CONTENT

Site	Biomass	Nitrogen (%)	Protein (Nx6.25) (%)
Bluewater	Shoot	1.16	7.25
	Root	1.04	6.50
	Standing Dry Matter	0.47	2.94
Fishtail	Shoot	1.12	7.00
	Root	1.26	7.88
	Standing Dry Matter	0.57	3.56
Mean	Shoot	1.14	7.13
	Root	1.15	7.19
	Standing Dry Matter	0.52	3.25

*Harvest date 9/6/82

TABLE 8: POTENTIAL WHOLE PLANT OIL SPECIES - GENUS *EUPHORBIA*

Content (% Dry Weight)

Species	Biomass	Oils	Polyphenols	Protein	Reference
E. cyparissias	Shoot	6.32	6.0	9.69	Buchanan et al 1978a
E. dentata	Shoot	2.2-9.7	3.9-5.8	15.2-22.1	Buchanan et al 1978b
E. esula	Leaves	9.3-13.8	7.3-21.3	-	Wiatr 1984
E. esula	Shoot	4.9	-	7.6	Hammaker et al 1983
E. lathyrus	Shoot	9.2	7.1	11.1	Buchanan 1978b
E. lathyrus	Shoot	4.4-6.2	-	-	Sachs et al 1981
	Shoot	6.43-8.55	-	-	Kingslover 1982
	Leaves	8	-	-	Sachs et al 1981
	Stem	<3	-	-	Sachs et al 1981
E. marginata	Shoot	4.7	-	9.7	Hammaker et al 1983
E. supina	Shoot	4.2	12.9	9.69	Buchanan et al 1978a
Range for all		<3-13.8	3.9-21.3	7.6-22.1	

TABLE 9: PROTEIN CONTENT IN OIL SEED CROPS, WHOLE PLANT BIOMASS, AND FORAGE CROPS

Plant	Protein Content (%)	Reference
Oilseed crops[1] (Protein after oil extraction)		
Sunflower	28-50	Peterson et al 1981
Safflower	25-45	"
Rapeseed	35-44	"
Whole plant biomass[2]		
Asclepias speciosa	10.9-11.6	Hammaker et al 1983
Asclepias syriaca	9.8-11.3	Buchanan et al 1978b
Chrysothamnus nauseosus	8.1- 8.7	Hammaker et al 1983
Euphorbia esula	7.6	Hammaker et al 1983
Euphorbia marginata	9.7	Hammaker et al 1983
Euphorbia dentata	15.2-22.1	Buchanan et al 1978b
Forage crops		
Alfalfa hay	17.0	Cullison 1982
Barley straw	4.1	"
Crested wheat grass	10.2	"

[1] Variation in protein content is based on the method of oil extraction and presence or absence of hulls.

[2] Prospective oil-producing species. Variation in protein content is based on different sampling dates, sites or both.

TABLE 10: CARBOHYDRATE PRODUCTION OF SELECTED CROPS[1]

CROP	YIELD[2] (bu/acre)	FERMENTABLE CARBOHYDRATE[3] (lbs/acre)
Corn	77.0	3353
Wheat	22.7	1097
Barley	39.0	944

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[1] Source: USDA Agricultural Statistics - 1980.

[2] All yield statistics are for Montana crops in 1979.

[3] Calculated as follows:
/Yield x (lbs/bu) x starch content/ _ 0.9 (glucose equivalents

Crop	Weight (lbs/bu)	Starch Content (%)
Corn	56	70
Wheat	60	72.5
Barley	48	45.4

TABLE 11: TOTAL FERMENTABLE CARBOHYDRATE IN _E. esula_

Site	Biomass	Fermentable Carbohydrate* (lbs/acre)
Bluewater	Shoot	280.6
	Root	303.6
	Total	584.2
Fishtail	Shoot	262.4
	Root	121.4
	Total	383.8
Mean	Shoot	271.5
	Root	212.5
	Total	484.0

* Total sugars + starch

TABLE 12: NET ENERGY YIELDS FOR SELECTED MONTANA CROPS

				Net Energy Yield (x 10^6 kcal/ha)		
SOURCE[G]	YEAR	CROP YIELD m.tons/ha	RESIDUE m.tons/ha	CROP[C]	RESIDUE[C]	TOTAL
Sugar Beet	1977	9.46[A]	2.27[B]	35.00	8.16	43.16
	1978	9.41	2.27	34.82	8.16	42.98
	1979	9.08	2.19	33.58	7.88	41.46
Barley[D]	1977	1.97	4.82	6.90	16.87	23.77
	1978	2.32	5.68	8.12	19.88	28.00
	1979	2.10	5.14	7.35	17.99	25.34
Corn[E]	1977	4.27	4.27	14.95	14.95	29.89
	1978	4.52	4.52	15.82	15.82	31.64
	1979	4.83	4.83	16.91	16.91	33.81
Winter Wheat[F]	1977	1.74	4.64	6.09	16.24	22.33
	1978	2.03	5.41	7.11	18.94	26.05
	1979	1.53	4.08	5.36	14.28	19.64

[A] Dry Weight Yield for Roots: D.W. = 21.2% F.W.

[B] Dry Weight Yield of Shoot Biomass: Shoot D.W. Yield = 24.1% of Root D.W. Yield

[C] Calculated from a Gross Energy Content of 3600 cal/g for Beet Residue, 3700 cal/g for Beet Crop and 3500 cal/g for All Other Sources

[D] Residue = 245% Crop Yield

[E] Residue = 100% Crop Yield

[F] Residue = 267% Crop Yield

[G] Yield Data From: Agricultural Statistics 1980 USDA

TABLE 13: SELECTED ENERGY VALUES

MATERIAL	GROSS HEAT VALUE cal/g	REFERENCE
Calotropis procera		
Whole plant biomass	4165	Erdman and Erdman 1981
Leaves	4099	Erdman and Erdman 1981
Leaves-hexane-extracted residue	10,003	Erdman and Erdman 1981
Leaves-methanol-extracted residue	4649	Erdman and Erdman 1981
Wheat straw	4722	Baumeister 1966
Wood	5000	Baumeister 1966
Anthracite coal	7156	Bolz and Tuve 1970
Lignite coal	3889	Bolz and Tuve 1970
Petroleum	10,506	Baumeister 1966
"Biomass"[A]	4700	Pimentel et al 1981
Cereal grain[A] (barley, corn, wheat)	3500	Pimentel et al 1981
E. esula[B]		
Leaves	4643-5192	Wiatr 1984
Oils	9483-10,095	Wiatr 1984
Polyphenols	4123-6033	Wiatr 1984
Residue[C]	4048-4705	Wiatr 1984
Perc oil	8778	Elliot 1981
LBL oil	8074	Elliot 1981
No. 2 Fuel oil	11,022	Elliot 1981
Sunflower Oil	9431	Peterson et al 1981
Safflower Oil	9445	Peterson et al 1981
Winter Rape Oil	9536	Peterson et al 1981
Diesel	10,818	Peterson et al 1981

[A] Calculated from Yield and Potential Energy Data

[B] Variation Due to Method of Dehydration

[C] Oil and Polyphenol Depleted Residue

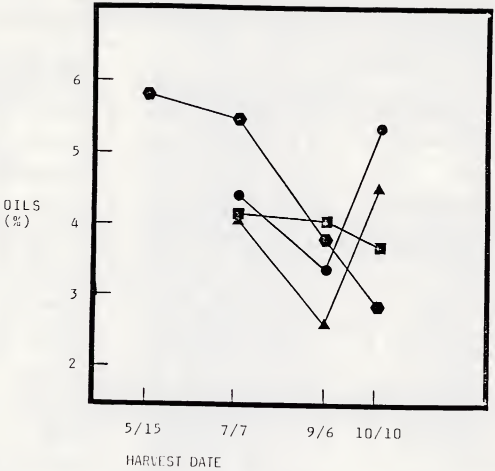

Figure 1. Seasonal Variation In Oil Content

● Bluewater Shoot

■ Fishtail Shoot

▲ Bluewater Root

⬢ Fishtail Root

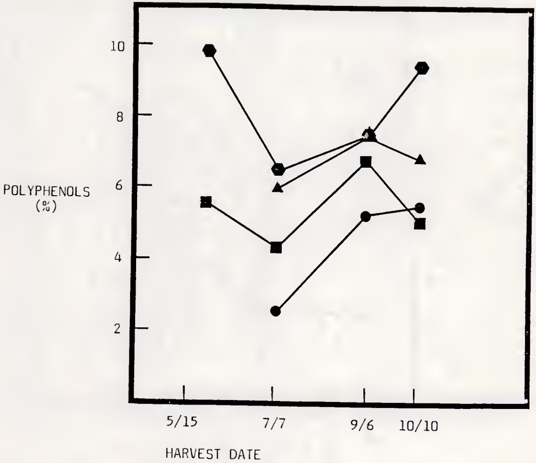

Figure 2. Seasonal Variation In Polyphenol Content

● Bluewater Shoot

■ Fishtail Shoot

▲ Bluewater Root

⬢ Fishtail Root

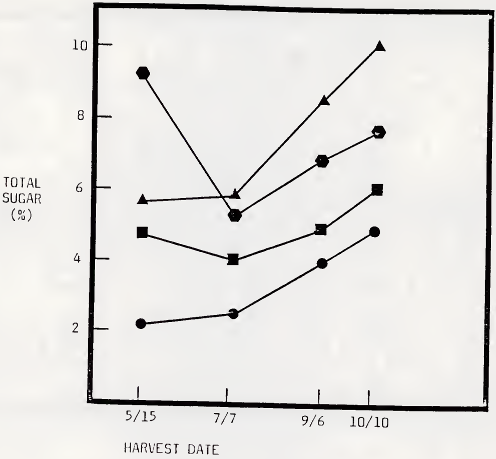

Figure 3. Seasonal Variation In Total Sugar Content

● Bluewater Shoot

■ Fishtail Shoot

▲ Bluewater Root

⬢ Fishtail Root

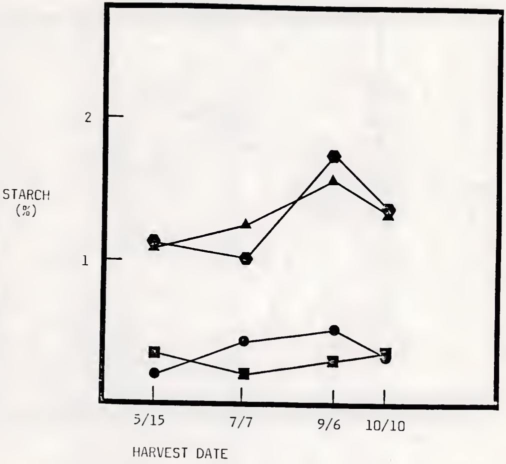

Figure 4. Seasonal Variation In Starch Content

● Bluewater Shoot
■ Fishtail Shoot
▲ Bluewater Root
⬢ Fishtail Root

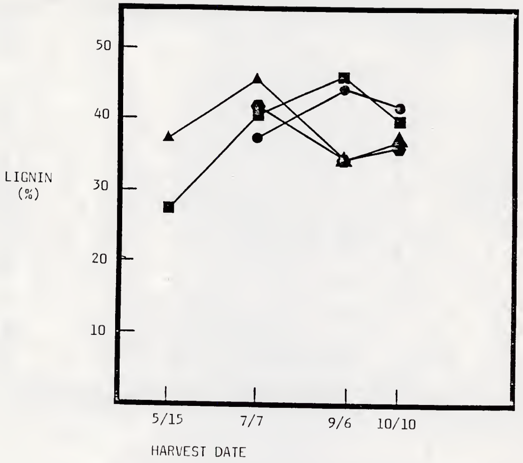

Figure 5. Seasonal Variation In Lignin Content

● Bluewater Shoot
■ Fishtail Shoot
▲ Bluewater Root
⬢ Fishtail Root

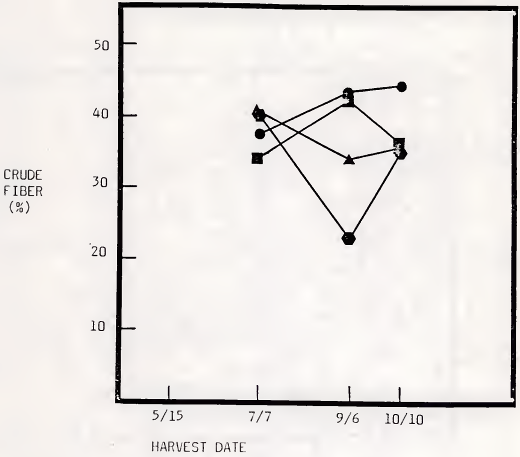

Figure 6. Seasonal Variation In Crude Fiber Content

● Bluewater Shoot

■ Fishtail Shoot

▲ Bluewater Root

⬣ Fishtail Shoot

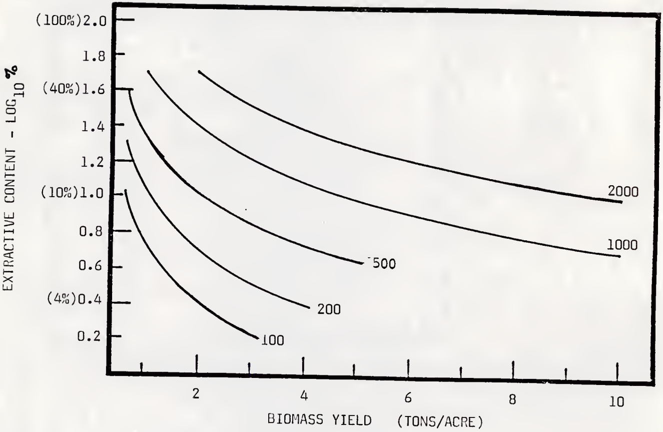

Figure 7. Relationship between biomass yield and extractive content. Curves indicate extractive yield in pounds per acre.

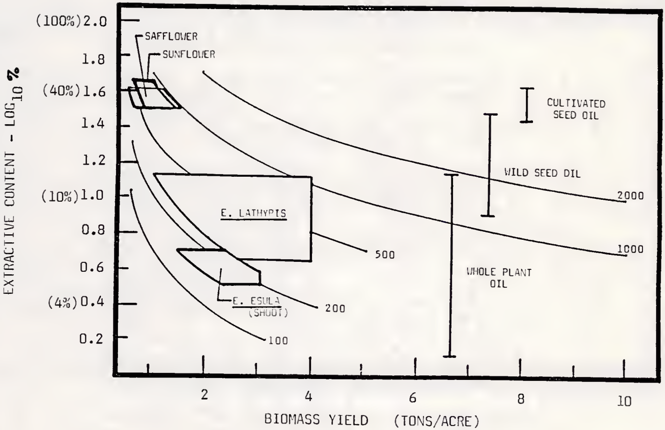

Figure 8. Yield envelopes for selected seed oil and whole plant oil crops. Curves (100, 200, 500, 1000, 2000) indicate oil yield in pounds per acre. Vertical bars give the range of oil content for cultivated seed oil, wild seed oil and whole plant oil derived from published values (NOTE: The position of these bars on the abscissa is irrelevant.) Yield envelopes have been truncated where limits to biomass yield or oil content are known.

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